Structure of Cirrus Properties and Its Coupling with the State of the Large-Scale Atmosphere

Contributors

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Research Highlight

The state of the large-scale atmosphere has a profound impact on the formation and maintenance of cirrus cloud events. However, the relationship between cirrus properties, including their structure and the synoptic regime in which they form, is still not quantitatively understood. This lack of knowledge represents a fundamental deficiency in our ability to accurately characterize cloud-climate interaction in global circulation models. Therefore, the objective of this research is to quantitatively connect the structure of observed radiative properties to a verifiable explanation of large-scale atmosphere and, furthermore, to the specific formation mechanisms for cirrus clouds.

A fundamental characteristic of cirrus occurrence and maintenance are the two different scales at which process occur. One is the large scale "envelope" of synoptic conditions in which the cirrus is either growing, approximately stationary, or decaying. The other is the small scale of individual generating cells which are always producing new ice crystals. It is obvious that the large scale influences the small scale; it is less obvious that small-scale variability influences the large scale. A recent study by Sardeshmukh and Sura (2007) looking at large-scale systems suggests that small-scale variability in diabatic heating does affect the large scale by increasing the amplitude of circulation structures on monthly to interannual timescales. Therefore, a more explicit representation of the small-scale variability and quantification of interactions between the two scales of processes is needed.

Our study outlines a stochastic approach that defines a framework to address these two fundamental aspects in the study of cirrus clouds occurrence and maintenance.

We analyze radar reflectivity measurements of cirrus cloud observed on April 19, 2004, obtained with the ground-based millimeter wavelength cloud radar (MMCR) at the DOE ARM Climate Research Facility (ACRF) Southern Great Plains site. To sample thoroughly the internal structure of cirrus properties, we consider time series of MMCR radar reflectivity at various depths into cloud relative to cloud top for both cirrus A and B. We find that the probability distribution functions (pdfs) of the radar reflectivity are time-dependent and non-Gaussian for a wide range of delay times at each depth level for both cirrus A and B.

Such time-dependent and non-Gaussian pdfs are known to result from interactions between the interwoven nonlinear and stochastic processes having different scales. The Fokker-Planck equation (FPE) provides a method to distinguish and quantify contributions of the large-scale, deterministic processes influencing the small scale and contributions of small-scale, stochastic processes influencing the large scale.

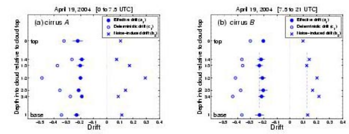

Figure 1. Values of the drift and diffusion coefficients of the Fokker-Planck equation derived from the MMCR radar reflectivity observations. The diffusion coefficient characterizes the small scale, fast stochastic processes in the system and can be associated with the in-cloud circulation. The noise-induced drift (crosses) presents stochasticity in the dynamics of the system, the influence of the small-scale noise on the slow, large-scale deterministic processes. See Table 1 for summary of the results.

Table 1: Summary of the results on identifying the structure of dynamical properties of cirrus based on stochastic analysis of radar reflectivity observations. Results are placed in the context of the synoptic environment and the thermodynamic stratification.

	Cirrus A	Cirrus B
Synoptic environment	Low pressure system (L)	High pressure system (H)
Thermodynamic stratification	Stable	Stable between d=0 (12 km) and d=1/4 (11 km) Neutral between d=1/4 (11 km) and d=3/4 (9 km)
Scales		
Large 2 hr (~100 km)	Structure of nucleation-growth-sublimation regions identified from the probability distribution functions (pdfs)	Structure of cirrus properties can not be identified from the pdfs
	— upper 33% — region of nucleation with long deposition times for vapor over condensed ice — cloud base — region of sedimentation and/or sublimation	
Intermediate 4-29 km	Gravity waves – top — (4-6 km) – upper 33% — (12-18 km) – d =3/4 — (29 km) and (25 km)	No periodicities found
Generating cells 1-2 km	Larger values of the effective drift $\tilde{D}_1^{eff.d.}$ at the top and the base versus middle 50% of the cloud (Figure (a)) — influence of the synoptic scale dynamics	Larger values of the effective drift $\tilde{D}_1^{eff.d.}$ at the base versus middle 50% of the cloud (Figure (b)) — influence of the synoptic scale dynamics
	Larger values of the noice-induced drift $\tilde{D}_1^{n.i.}$ that represents the stochasticity of the system in the middle 50% versus – in both the upper and the lower 25% (Figure (a)	– in both the upper 33% and the lower 25% (Figure (b) This is in accordance with what is expected from the ice crystal growth and deposition region.
	Larger values of the noice-induced drift $\tilde{D}_1^{n.i.}$ in the middle 50% of cirrus A versus $\tilde{D}_1^{n.i.}$ in the middle 50% of cirrus B, which is in accordance with intensive ice producing generating cells in A (Figure (a,b)	

Table 1. Summary of the results on identifying the structure of dynamical properties of cirrus based on stochastic analysis of radar reflectivity observations.

We apply the FPE method to study the structure of cirrus properties at the scale of (60 s) 1-2 km which is the scale of the generating cells (Table 1). We find that the evolution of the time-dependent probability distribution functions is governed by the Fokker-Planck equation with linear drift and stochastic diffusion with state-dependent, multiplicative noise. The drift coefficient can be identified tentatively with the large-scale deterministic forcing (see Figure and Table 1).

At intermediate scales, using the power spectrum and autocorrelation function analyses of radar reflectivities, we find periodicities in cirrus A and no periodicities in cirrus B (Table 1). These spatial scales suggest internal gravity waves that occur in cirrus A. The hypothesis of existence of gravity waves is supported by the stable thermodynamic stratification found in cirrus A. The absence of periodicities and the neutral stratification are associated with convection from about 9 to 11 km during cirrus B.

At large scales (100 km), we find that the pdfs of the radar reflectivity in cirrus A for delay times of 2 hr exhibit behavior that is consistent with the structure of cirrus based on aircraft in situ measurements (Heymsfield and Miloshevich, 1995) and with results from ground-based Raman lidar studies of cirrus (Comstock et al, 2004).

Even though based on a single cirrus cloud, our study presents initial answers to the problem of the coupling between the structure of cirrus cloud properties and the state of the large-scale atmosphere. Furthermore, it demonstrates the potential to trace back the structure of cirrus properties to cirrus formation mechanisms. Further research will focus on generalization of the findings in this study, with results anticipated to provide recommendations to the climate model to treat cirrus differently owing to different synoptic and/or other different physical forcing.

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Reference(s)

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Working Group(s)
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